Paper Accepted: Lightwave Telecommunications Systems

Wavelength Division Multiplexed Local Area Networks

L. G. Kazovsky, C. Barry, M. Hickey, C. Noronha, P. Poggiolini

1991 N00014-91-J-1857

The advent of new services, such as multimedia communications, high-volume file transfer, high-definition image transmission, video/audio retrieval, and others, has created a need for high speed data networks. Future networks are expected to support, in an integrated fashion, services with highly diverse traffic requirements. Due to the high data rates involved, such networks will use optical fiber as the transmission medium.

It has been recognized that current network topologies, employing single shared channels to provide connectivity between the nodes, are not adequate to provide these new services, thus creating the need for multi-channel networks. One way to realize multiple channels on the optical fiber is through the use of Wavelength-Division Multiplexing (WDM); this method has the additional advantage that, by employing tunable transmitters and/or receivers, the network topology can change dynamically in time.

This paper will focus on WDM Networks. Following a discussion of the possible network topologies, we investigate the technological issues related to the implementation of such topologies, and describe some experimental implementations reported in the literature.

BROADBAND SERVICES

In addition to existing services (remote logins, file transfer, voice), high-speed local area networks will be required to support broadband services. Broadband interactive services have been classified by CCITT Recommendation I.121 [1] into the following categories:

Conversational Services: real-time end-to-end information transfer, like video-telephony, high-definition image transfer, high-speed data transfer;

Messaging Services: communication via store-and-forward, like multimedia mail;

Retrieval Services: retrieval of information stored in databases, like video on demand, or high-fidelity audio.

To provide the services described above, a network will have to handle both stream traffic (i.e., uncompressed video and audio) and bursty traffic (i.e., variable bit rate video, bursty data, etc), at a range of data rates which spans several orders of magnitude. Some data rates required to provide broadband services are shown in Fig. 1.

In this paper, we will briefly comment on current network topologies and their limitations, and will discuss the alternatives that can be provided by optical technology. After a discussion of the technological issues relevant to the implementation of WDM optical networks, we will describe some experimental WDM networks reported in the literature.

NETWORK TOPOLOGIES

Current Topologies

Commercially available Local Area Networks (LANs) are usually organized as buses or rings, with data rates ranging from 10 Mb/s (Ethernet) to 100 Mb/s (FDDI). New standards, like the IEEE 802.6 Metropolitan Area Network, will push data rates up to 150 Mb/s and above. Fig. 2 illustrates the topologies for these networks. Ethernet is a "broadcast" network: packets are transmitted on a common cable (bus) and are received by all nodes. A particular node will discard all packets not addressed to it. FDDI ("Fiber Distributed Data Interface") is a ring composed of point-to-point links where a "permit to transmit" (token) circulates; only the node with the token can inject new information on the network. Data circulates in the ring and eventually reaches the destination node. The IEEE 802.6 Metropolitan Area Network (MAN), also known as DQDB ("Distributed Queue Dual Bus") is composed of two slotted buses where information flows in opposite directions; access to the slots on those buses is regulated by a reservation system, intended to make the communications network operate as a distributed queue. The main problem with these architectures is that connectivity between the nodes is provided by a small number (one, or two in the case of IEEE 802.6) of shared channels. Therefore, the electronics on each node has to operate at the network aggregate speed. On the average, the maximum capacity available to each node is C/N, where C is the channel capacity and N is the number of nodes; in practice, this number is even lower due to the overheads associated with the medium access protocol. These topologies are clearly inadequate to provide the broadband services described above. Multiple-channel topologies are needed, and due to the data rates involved, optical transport mechanisms are an excellent choice.

Future Networks

Due to high data rate requirements, single channel networks (like buses or rings) will not be able to provide the expected level of service because each node would have to operate at the aggregate speed of the network. This is neither possible (due to the speeds required) nor desirable (due to the resulting low efficiency). The network, therefore, will have to provide multiple concurrent channels. In an optical network, this can be accomplished either by providing multiple fibers between the nodes, or by creating multiple channels on the same fiber. The latter can be done by modulating each data stream on a different wavelength.

The main advantage of using WDM to provide multiple channels, as opposed to having multiple fibers, is that, with the use of tunable transmitters and/or receivers on the nodes, the *logical network topology* becomes independent of the *physical network* *topology*, as long as all nodes have access to all wavelengths. This allows greater network flexibility as channels can be dynamically allocated according to the traffic requirements. This process is illustrated in Fig. 3, where a four-node network is shown. The nodes are connected to a star coupler, as indicated in Fig. 3a; this star coupler combines the light from all transmitters and makes it available to the receivers. By properly assigning wavelengths to receivers, different logical topologies can be created, as indicated in Figs. 3b and 3c.

In general, a node may have multiple transmitters and receivers. However, the number of transmitters and receivers present at each node is typically much less than the number of nodes on the network. Connectivity can therefore be provided in two ways: (i) by having a multi-hop network, i.e., if node A does not have a direct channel to node B, data from A to B will be sent via a number of intermediate nodes; (ii) by time division multiplexing (TDM) the use of each wavelength. Option (ii) is implemented by assigning to each source-destination pair a time interval on a certain wavelength; communication is always single-hop, at the expense of added delay. There are several methods to assign source-destination pairs to specific wavelengths; these methods range from classical multiple-access algorithms to fixed-assignment TDM.

Several algorithms, intended to dynamically control the use of the WDM channels, have been proposed [3-9]. These algorithms can be divided into two general classes, which directly correspond to the two connectivity options described above:

1) Slow tuning: The channel re-allocation is done very infrequently, and the network might even be put off-line during the reconfiguration process. Communication between the nodes is multi-hop, as described by option (i) above. The network control then becomes an optimization problem, whereby the network topology and the flow assignment are selected to minimize a specific objective function. Possible objective functions are the average delay [3], the average path length under deflection routing [4] and the maximum flow over all links [5,6]. Due to the complexity of the problem, one has to use either numerical methods [3,4] or heuristic decomposition into tractable subproblems [5,6] in order to find the "best" topology.

2) **Fast tuning:** It is assumed that the tuning time for the transmitters and/or receivers at the nodes is negligible. The WDM network is seen essentially as a fast packet switch; connectivity is provided as indicated by option (ii) above. When the number of users is much larger than the number of available WDM channels, traditional multiple access schemes (ALOHA, CSMA) can be adopted to regulate the access to the channel [7]. Since each node has a tunable transmitter and a tunable receiver, one of the channels is reserved for control, and idle nodes keep their receivers tuned to this control channel. In [8], a more generic configuration with each node having multiple transmitters and receivers is considered. Using standard Markov chain arguments, the authors derive an approximate upper bound on the performance of the network. In [9], non-uniform traffic is studied; the nodes are considered to be synchronized.

TECHNOLOGICAL ISSUES

Optical Transmitters and Receivers

Architectural concepts developed for conventional radio receivers and transmitters have been widely used in the field of optical transceivers. As with their radio counterparts, optical transmitters can modulate coherent light in amplitude (ASK), frequency (FSK) or phase (PSK). Receivers can be divided into two categories: **direct detection and coherent,** as shown in Fig. 4. In direct detection receivers (Fig. 4a), the received light signal is applied directly to the photodiode. Since photodiodes are essentially broadband devices and respond only to the signal power, direct detection receivers can be used to demodulate ASK and, with filtering, wide-deviation FSK. A coherent receiver, shown in Fig. 4b, employs a local oscillator (LO) laser tuned to an optical frequency near that of the transmitted signal. The use of an LO frequency equal to that of the signal frequency is known as homodyne detection; the use of an LO frequency which differs from the signal frequency is referred to as heterodyne detection. The received signal and the local laser fields are added with a fiber combiner and coupled to a photodiode. Because the output current from a photodiode is proportional to the square of the incident electric field, the photodiode acts a mixer and produces an intermediate-frequency (IF) current at the difference frequency of the signal and the LO. Demodulation of the IF current recovers the transmitted data. A problem that must be faced with coherent receivers is polarization control: the state of polarization (SOP) of the received signal must be aligned with the SOP of the light from the local oscillator laser to create the desired interaction between the two.

Realization of the full potential of a WDM network requires electronically tunable transmitters and/or receivers. Tunable transmitters can be made using tunable lasers. Since photodiodes respond nearly equally to the entire range of wavelengths used for communication (from 1270 to 1350 nm and from 1460 to 1600 nm), a direct-detection tunable receiver can be realized by placing a tunable optical filter before the conventional direct-detection receiver shown in Fig. 4a. Tunable coherent receivers can be realized by using tunable lasers as local oscillators, because only the specific wavelength matching the wavelength of the local oscillator will be demodulated.

In the following, we discuss tunable lasers and tunable filters, needed to build tunable transmitters and receivers. We also discuss the issues of polarization control in coherent receivers and frequency stabilization of the network.

Tunable Lasers

Lasers can be tuned by providing a wavelength-tunable element inside the laser cavity. Generally speaking, there are two kinds of tunable lasers: **external cavity** and **integrated** lasers. The tuning method generally represents a tradeoff between tuning speed, linewidth, and tuning range. Moreover, depending on the method, the tuning can be either continuous or discrete over a certain range.

1) **External cavity** tuning methods provide very low linewidth (due to the long cavity) and large tuning ranges, at low to moderate speeds. Tuning is frequently discrete (i.e., the device can generate only a discrete set of wavelengths inside the tuning range). Acousto-optically tuned elements in the cavity yield tuning ranges on the order of 70 nm at 3 μs tuning time [10], while electro-optic elements can reach a range of 7 nm at 100 μs tuning time, with resulting laser linewidths on the order of 60 kHz [11]. However, these configurations usually demand precise alignment between the laser and the external cavity and therefore are difficult to implement

2) **Integrated** tunable lasers can potentially be tuned at very high speeds (nanoseconds for some devices; although practical tuning speeds for those devices are still being investigated) at the expense of tuning range and linewidth. Some devices are also capable of continuous tuning over a range of frequencies. There are two basic kinds of integrated tunable lasers: (multi-electrode) distributed feedback (DFB) and (multi-electrode) distributed Bragg reflector (DBR). Two-electrode DFB lasers with continuous tuning ranges around 3.3 nm and linewidths of 15 MHz have been reported [12]. Three-electrode DFB lasers exhibit lower linewidths (500 kHz) at the expense of a lower tuning range (2 nm) [13]. Three-section DBR lasers can have higher tuning ranges (8-10 nm) with quasi-continuous tuning, exhibiting linewidths on the order of tens of MHz and tuning times on the order of microseconds [14]. Continuous tuning can be achieved for smaller ranges (2-4 nm) at nanosecond tuning times [15], with increased linewidths. A more detailed discussion of the device characteristics and of the several tuning methods can be found in [15-16].

Table I presents a summary of the important tunable laser characteristics. The most important conclusion which can be drawn from Table I is that the main drawback of tunable lasers is tuning range, and this is what will finally limit the number of WDM channels a laser can resolve.

Table I: Tunable Laser Characteristics

Technology	Acousto Optics	Electro Optics	2-Section DFB	3-Section DFB	3-Section DBR	3-Section DBR
Tuning Range	70 nm	7 nm	3.3 nm	2 nm	4.4 nm	2 nm
Kind of Tuning	discrete	discrete	continuous	continuous	continuous	continuous
Laser Linewidth	n.a.	60 kHz	15 MHz	500 kHz	1.9 MHz	2.5-6.5 GHz
Speed	3 μs	100 μs	n.a.	n.a.	10 μs	15 ns

Tunable Filters

Wavelength filtering can be achieved by the following mechanisms [17]: (i) wavelength dependence of interferometric phenomena (Fabry-Perot and Mach-Zehnder filters); (ii) wavelength dependence of coupling between modes, caused by external perturbations (electro-optic and acousto-optic filters) and (iii) resonant amplification in active semiconductor devices. Table II, adapted from [17], gives the characteristics of tunable filters realized by each method.

Table II: Tunable Filter Characteristics

Technology	Fabry-Perot	Acousto-Optics	Electro-Optics	Active Semiconductor
Tuning Range (nm)	50	400	10	1-4
Bandwidth (nm)	<0.01	1	1	0.05
Number of Channels	100s	100s	10	10s
Loss (dB)	5	5	5	0
Tuning Speed	ms	μs	ns	ns

The main conclusion which can be drawn from Table II is that, although it is possible to build direct-detection tunable receivers, current tunable filter technology limits either the tuning speed or the tuning range that can be achieved.

Polarization Control

Coherent receivers require that the polarization of the local oscillator matches the polarization of the incident light; otherwise, the useful signal generated at the photodiode can be attenuated or even fade completely. As light propagates through conventional single-mode optical fiber, its polarization is transformed to an arbitrary, generally elliptical, state by unavoidable small perturbations in the fiber. These perturbations include small index variations in the fiber and time-varying environmental factors such as temperature and vibration. There are several approaches for matching the signal and local oscillator polarizations:

1) **Polarization-Maintaining Fiber and Connectors [18]:** By appropriately shaping or stressing the fiber core, it is possible to produce special fibers that do not change the polarization of the transmitted light, provided that the state of polarization of the light launched on the fiber is aligned with one of the main axes of the fiber. Fig. 5 illustrates some polarization-maintaining fibers.

2) **Polarization-Diversity Receivers [19]:** After (or before) mixing the light from the local oscillator with the incoming light, polarization-diversity receivers divide the resulting mixture into two orthogonal polarizations and detect them separately. After photodetection and demodulation, the resulting signals are combined. The combined signal is independent of the state of polarization of the received light. Fig. 6 illustrates one such approach [19].

3) **Polarization Switching [20]:** During each bit, the polarization of the transmitted light is switched between horizontal and vertical (i.e., it stays half of the time in the vertical polarization, and the other half in horizontal). With this scheme, the receiver is simpler than a polarization-diversity receiver. However, the transmission is more complex, and a 3 dB penalty on the receiver sensitivity is introduced.

4) Polarization Tracking [21]: In the same way as a PLL tracks the frequency of its input signal, it is possible to have the local oscillator track the polarization of the incoming light, at a cost of increased receiver complexity.

Frequency Stabilization

Absolute and relative optical frequency stabilization may be required in multichannel optical systems with tight channel spacing.

1) Absolute frequency stabilization: These techniques typically involve frequency locking to a stable atomic or molecular absorption phenomenon. In [22], an absolute reference is achieved by locking a GaInAsP DFB laser to an atomic transition of Ar at 1.290 μm. The resonant frequencies of a tunable Fabry-Perot interferometer, locked to the absolute reference, are then used to frequency-lock transmitter lasers as shown in Fig. 7. A very compact, 4.5 x 2 x 2 cm, implementation of an absolute reference, reported in [23], uses absorption in acetylene to provide a 1.53159 μm references with frequency spacings of 9 GHz.

2) Relative frequency stabilization: One possible technique of obtaining a relative frequency stabilization is to use FM sidebands of an FM modulated master laser to provide 30 discrete frequency references with spacing of 500 MHz [24]. Another scheme, shown in Fig. 8, employs optical phase locking to the sidebands of RF phase modulated master laser [25]. Twenty-one discrete frequencies were provided with a frequency stability of 3 kHz.

WDM NETWORK EXPERIMENTS

The last five years have seen a steady transition of WDM experiments from proof of concepts to the integration of these concepts in experimental networks, with field trials planned in the near future. Several notable experiments illustrate the progression of this technology: demonstrations of single channel transmission multi-gigabit data rates [26-

27], broadcast of 100 direct detection channels [28], 16 channel coherent broadcast experiment [29], computer controlled tuning of an 8 channel coherent experiment [30], and demonstration of a fully engineered coherent broadcast experiment [31]. The following two sections are devoted to descriptions of recent experimental demonstrations of WDM optical metropolitan and local area networks, both direct detection and coherent.

Direct Detection WDM Optical Networks

Several experiments are currently investigating direct detection WDM networks. These experimental networks use direct detection optical receivers and tunable optical filters for channel selection. Direct detection technology was chosen for its reduced cost and complexity. Two of these experiments are described below.

TeraNet

TeraNet [32] is a experimental network being developed to study all seven layers of the OSI standard. The network provides either 1 Gb/s ATM packet-switched or 1 Gb/s circuit-switched access using a passive star topology, as shown in Fig. 9a. A hybrid multiple access scheme combines wavelength-division-multiplexing and subcarrier frequency division multiplexing to divide the available optical bandwidth. This method of multiple access reduces the bandwidth requirements on the optical filters but still allows the use of additional channels through electronic means.

The transmitters, located in the media interface units (MIU's), utilize DFB lasers. Each user is assigned a unique address consisting of a specific wavelength and a subcarrier multiplexed frequency. Wavelength channels are spaced by 1.5 nm, or 187 times the bit rate. Each wavelength also supports 4-6 subcarrier channels. The subcarrier modulation format can be either BPSK or QPSK while the subcarriers amplitude modulate the optical signal.

The receivers use fiber-optic Fabry-Perot (FFP) tunable filters, also located in the MIU's, to select wavelengths. Subcarriers are selected by electronic filtering.

A packet switched network, conforming to the ATM standard [33], is implemented using one network interface unit (NIU) and two MIU's per user through a multihop architecture. For eight users, this configuration is illustrated in Fig. 9b The network can be configured to support up to 64 users. Interfaces are also being developed for SONET and HIPPI. A limited campus field trial is planned for 1992.

RAINBOW Network

The RAINBOW network [34] is a metropolitan area network designed to cover a diameter of 55 km. This network connects 32 IBM PS/2's through a 32x32 passive star coupler and allows the computers to communicate circuit-switched data at a rate of 200 Mb/s/node, as shown in Fig. 10. Each computer is equipped with its own fixed frequency transmitter and tunable optical receiver mounted on plug-in computer cards.

The optical transmitters utilize directly modulated distributed feedback (DFB) laser diodes. The optical channel spacing is roughly 1.6 nm, or 1040 bit rates. This channel spacing is wide enough so that temperature control is adequate for frequency stabilization. The modulation format is on/off keying (OOK).

Wavelength selection is accomplished with a tunable fiber Fabry-Perot filter. The interferometer cavity spacing is varied piezoelectrically to achieve a tuning speed of 2 ms over the tuning range of 50 nm.

The signalling protocol for coordinating the retuning of the optical receivers is a simple in-band polling procedure. This method is simpler than a faster out-of-band protocol, which would require a separate signalling channel.

Experimental results reveal that a power budget of 8.5 dB with a 3 dB margin is typically achieved. This budget would allow a network diameter of 28 km

Coherent WDM Computer Networks

The direct-detection experiments described above demonstrate the potential of WDM computer networks and show that increasing network performance will require improved power budgets, tighter channel spacing, increased tuning speeds or new network architectures. Coherent technology is one option of increasing the power budget and decreasing the channel spacing. Below we describe one WDM coherent experiment, and in the next section we will discuss STARNET, a coherent WDM network being implemented at Stanford University.

UCOL

UCOL is being developed as an ultra-wideband coherent optical local area network [35]. This network has network interface units/access control units (NIU/ACU's) that communicate on 20 wavelength division multiplexed optical channels over a passive star topology, as indicated in Fig. 11. The user can access each channel through a time division multiplexing access mode (UCOL ATM SWITCH). This technique supports data rates from a fraction of a Mb/s up to 155 Mb/s. The frequency reference for all transmitters and receivers is provided over a separate star coupler by a reference generator block (RGB). The reference frequencies are generated by modelocking an external cavity semiconductor laser. The RGB is shown only in one station in Fig. 11; however there could be multiple RGB's housed in other stations for redundancy. Channel spacing is 3.6 GHz, or about 23 Rb, minimum.

The transmitters are external cavity lasers, tunable over 1 nm in the 1.5 nm wavelength window. DPSK modulation is accomplished with an external $LiNbO_3$ modulator.

The receivers are polarization diversity, delay line DPSK demodulators. The transmit power is set for operation with a BER of 10^{-6}. Error-correcting codes are then used to decrease the BER to a value less than 10^{-13}.

STARNET: A COHERENT BROADBAND OPTICAL NETWORK

The foregoing network experiments have shown the feasibility of relatively dense WDM networks. However, these experiments have not addressed the need to support all the heterogeneous data traffic types as outlined in the introduction of this paper. STARNET [36] is a new broadband optical local area network (BOLAN) architecture. The STARNET architecture offers *all* users *both* a moderate-speed packet switched network and a high-speed broadband circuit interconnect based on a WDM transport facility, as shown in Fig. 12. As a result, the STARNET architecture efficiently supports diverse types of traffic. An experimental demonstration of STARNET is currently under development in the Optical Communications Research Laboratory at Stanford University. The initial STARNET experiment will interconnect four workstations through a 4x4 passive star coupler. The data rate for the broadband circuit switched network is 3 Gb/s/station. The packet switched network data rate is 100 Mb/s. The total throughput of the experimental STARNET is more than 12 Gb/s.

STARNET Architecture

STARNET's physical topology is shown in Fig. 3a. Each node of the network is optically connected to all other nodes via a passive optical star. Each node has a two-fiber connection with the star: one fiber carries the nodes' traffic to the star and the other fiber carries all the network traffic to the node.

Using an appropriate multiplexing strategy discussed below, each node transmitter transmits *two independent data streams*, stream 'C' (Circuit data) and stream 'P' (Packet data), as depicted in Fig. 13. Each node has a tunable receiver that can be tuned to any transmitter and decodes the 'C' stream thus enabling a broadband circuit interconnect among all the nodes. In addition, every node is equipped with a fixed receiver which decodes the 'P' stream *of the previous node in the frequency comb*, as shown in Fig. 14. The first node of the chain is equipped with a receiver that decodes the 'P' stream of the last node. In this manner, a unidirectional store-and-forward logical ring topology is formed. This topology is similar to the FDDI topology shown in Fig. 3b.

The fact that the node transmitter is capable of sending two concurrent data streams not only avoids the need for another optical transmitter, but also prevents the formation of a second comb of carriers which would waste optical bandwidth. A broadcast mode of operation is achieved by having multiple receivers tune to the broadcasting transmitter.

Extensions to the basic node configuration include equipping each node with a transmitter capable of multiplexing one 'C' stream with two 'P' streams. Fig. 15 shows that this connectivity permits a bidirectional store-and-forward chain. Moreover, this extended configuration supports high-speed packet traffic by allowing multihop networks.

STARNET Physical Implementation

The experimental STARNET implementation connecting four workstations through a 4x4 passive star coupler is shown in Fig. 16. Each node is comprised of a transmitter, a 3 Gb/s broadband receiver for the circuit interconnect, and a 125 Mb/s receiver for the packet-switched network. Since four 3 Gb/s signals are combined through the star, the total throughput of the network is 12 Gb/s. The network operates at a center wavelength of 1319 nm over conventional single mode fiber with a network diameter of 4 km.

Fig. 17 shows a STARNET transmitter. The laser source is a 25 mW, 1319 nm Nd:YAG laser. The light carrier passes through an isolator and is then coupled into a conventional single mode fiber. Subsequently, the light passes through a 50% splitter; half the power is sent to the external modulator, while the other half is used as the LO for the packet-switched network receiver. The external modulator is a $LiNbO_3$ dual phase/amplitude modulator. The 3 Gb/s circuit switch data is PSK modulated on the optical carrier. The 100 Mb/s packet data is 4B/5B encoded and then ASK modulated on the optical carrier at 125 Mb/s by modified FDDI hardware in the workstation. After modulation, the optical signal is sent to the star.

The combined node receiver structure is shown in Fig. 18. The optical signals of all the nodes on the network are combined through the star and arrive at each receiver where they are first split between the main 3 Gb/s heterodyne PSK receiver and the auxiliary 125 Mb/s heterodyne ASK receiver.

The PSK receiver uses a thermally tunable Nd:YAG laser as the LO. The polarization of the LO light is manually aligned with the polarization of the network signal and then both signals are combined with a 3 dB coupler. The mixed optical signal is applied to a PIN photodiode with a low-impedance front-end. The resulting electronic signal is centered around an IF of 8 GHz. The signal is then mixed with a 8 GHz RF local oscillator to bring it down to baseband. A portion of the baseband signal is used to maintain phase lock of the receiver [27]. The remainder of the baseband signal is low-pass filtered to recover the 3 Gb/s data. The system is designed to ensure a BER of 10^{-9} with a 10 dB system margin.

The ASK receiver uses the transmitter laser as the LO. After polarization alignment and 3 dB coupling, the ASK heterodyne optical signal is sent to a PIN photodiode with a low-impedance front-end amplifier. The resulting IF signal is squared to remove the phase modulation and sent to a low-pass filter to recover the baseband 125 Mb/s data. The data is then decoded by the FDDI hardware in the workstation.

The following is a discussion of some of the design decisions that were made for the initial STARNET experiment.

1) **Modulation Format:** PSK modulation is used for the 3 Gb/s broadband circuit. Heterodyne PSK was chosen for the 3 Gb/s interconnect because of its superior receiver sensitivity, 3 dB better than heterodyne FSK and 6 dB better than heterodyne ASK.

2) Transmitter/Modulator: Since heterodyne PSK detection is used, lasers with low laser linewidths are required [37]. Nd:YAG lasers were selected for their ultra-narrow linewidth, excellent frequency stability, and large optical power output (25mW). In addition, the transmitter is tunable. The tunability is used for network configuration flexibility and fault tolerance, rather than for wavelength switching.

The logical ring topology chosen for the packet network enables the use of commercially available FDDI hardware to implement the packet-switched segment of the network. The physical layer of the packet network is different from that of FDDI: instead of directly modulated LED transmitters and PIN photodiode receivers, we use externally modulated laser transmitters and coherent heterodyne ASK receivers. Nevertheless, once the frequency comb has been established, all but the physical layer of the packet network are compatible with FDDI.

3) Network Frequency Allocation: Node transmitter frequencies are allocated in a bandwidth efficient manner [38], as shown in Fig. 19. Fig. 20 shows the signal spectrum at the IF stage of the packet network fixed receiver. Note that the previous and next node are visible although at different IF frequencies. The minimum optical channel spacing is 8 GHz, resulting in packet network IFs of 8 GHz or 16 GHz depending on the position of the receiver node. The IF for the 3 Gb/s broadband circuit is 8 GHz for all nodes and is set by the tunable receiver LO. For the four node experiment, the range of transmitter frequencies is 32 GHz. At 1319 nm center wavelength, this results in an extremely dense optical channel spacing of just 0.04 nm, or 2.67 bit rates. Although the channel spacing is very narrow, less than 1dB of channel crosstalk power penalty is incurred [39].

4) Tunable Receiver: Key elements of the tunable receiver are the tunable laser LO, photodiodes, and RF demodulators. The tunable receiver LO is also a Nd:YAG laser, chosen for its ultra-low linewidth. Unfortunately, the narrow linewidth is accompanied by slow thermal tuning (several seconds) and a small tuning range (40 GHz). A

PIN photodiode with a low-impedance front-end amplifier is used for photodetection of the heterodyne PSK signal. The greater sensitivity of a balanced receiver is sacrificed for the reduced cost and complexity of the single ended receiver. Integrated balanced receivers are not yet readily available with a bandwidth of 8 GHz. The IF demodulator utilizes commercially available microwave components.

5) Frequency Stabilization: STARNET uses a novel approach to achieve the relative frequency stabilization of the network. The fixed receiver must keep its LO tuned to the previous node in the frequency comb. In STARNET, the LO of the fixed receiver is also the node transmitter laser. Therefore, the frequency control operated by the fixed receiver to keep its LO locked on the previous node carrier also establishes relative frequency stabilization between the two nodes. Since this is done by all the nodes, each node is locked to the previous one and overall network frequency stabilization is achieved. Similar experiments with semiconductor lasers have shown promising results [40].

6) Polarization Control: Polarization control of the initial STARNET experiment is manual. This reduces the complexity of the receiver. A more mature implementation will require an automatic polarization control strategy such as polarization diversity, polarization tracking receivers, or polarization maintaining fibers.

SUMMARY AND CONCLUSIONS

The characteristics of the WDM network experiments discussed in this paper are summarized in Table III. As indicated by the table, coherent networks achieve denser channel spacing and higher data rates at the expense of added complexity.

Table III: WDM Network Experiments

	TERANET	RAINBOW	UCOL	STARNET
Modulation Format	ASK	ASK	DPSK	PSK
Data Rate	1 Gb/s	200 Mb/s	155 Mb/s	3 Gb/s
Channel Separation	187 Bit rates	1040 Bit rates	23 Bit rates	2.7 Bit rates
Kind of Receiver	Direct Detection	Direct Detection	Coherent	Coherent
Tunable Element	Fabry-Perot Filter	Fabry-Perot Filter	Laser	Laser
Frequency Stabilization	Thermal	Thermal	External Reference	Provided by the architecture
Polarization Control	Not needed	Not needed	Polarization-Diversity	Manual
Receivers per Node	2/tunable	1/tunable	1/tunable	1/tunable 1/fixed
Transmitters per Node	2/fixed	1/fixed	1/tunable	1/fixed
Extra Features	Multiple subcarrier channels		Wide range of data rates supported	Lower speed packet network imbedded

Multi-Gigabit/s broadband networks are required for future high-speed applications such as video conferencing and supercomputer interconnection. In addition, these future networks must also handle current low-speed applications such as electronic mail and file transfer. As indicated by Table III, direct detection and coherent technology both offer solutions to the networking of many high-speed channels using WDM.

Although experimental WDM systems take advantage of the huge bandwidth of the optical fiber, both optical filter and laser tuning speeds are not yet fast enough to support very high-speed packet switched data. One solution to this problem is offered by the STARNET. The STARNET architecture provides *two logical networks*, a high-speed broadband circuit switched network *simultaneously* with a moderate-speed packet switched network. A four node experimental STARNET is being constructed at Stanford University. It will interconnect four workstations with a data rate of 3 Gb/s/node for the circuit switch network and 100 Mb/s for the packet switch network. Total throughput for the experimental STARNET will be over 12 Gb/s.

Many challenges are yet to be resolved before multi-Gigabit/s optical networks become practical. Among these challenges are the development of fast tunable and narrow linewidth lasers, tunable filters, automatic frequency selection, frequency stability of the network, design of network protocols efficient for high speed bursty and continuous traffic, and selection of network topologies which optimize both throughput and latency. Continuing progress in the field of coherent WDM systems indicates that this technology may play a major role in the implementation of multi-Gigabit/s networks of the future.

ACKNOWLEDGMENT

Support for the STARNET experiment is provided by the National Science Foundation, through Grant No. ECS-9111766, and by the Office of Naval Research, through Grant No. N00014-91-J-1857.

References

[1] CCITT Recommendation I.121, "Broadband Aspects of ISDN," Blue Book, fascicle III.7, pp. 34-61, Melbourne 1988.

[2] F. Tobagi, "High-Speed Networking and B-ISDN," INFOCOM 1991 Tutorial, Bal Harbour, Florida, April 9-11, 1991.

[3] J. Bannister, L. Fratta, M. Gerla, "Topological Design of the Wavelength-Division Optical Network," *IEEE INFOCOM 1990*, San Francisco, June 3-7, 1990.

[4] J. Bannister, L. Fratta, M. Gerla, "Routing in Large Metropolitan Area Networks Based on Wavelength-Division Multiplexing Technology," in *High-Capacity Local and Metropolitan Area Networks - Architecture and Performance Issues*, edited by G. Pujolle, Springer-Verlag, 1990.

[5] J.-F. Labourdette and A. Acampora, "Wavelength Agility in Multihop Lightwave Networks," *IEEE INFOCOM 1990*, San Francisco, June 3-7, 1990.

[6] J.-F. Labourdette and A. Acampora, "Partially Reconfigurable Multihop Lightwave Networks," *IEEE GLOBECOM 1990*, San Diego, Dec. 2-5, 1990.

[7] I. Habbab, M. Kavehrad and C. Sundberg, "Protocols for Very High-Speed Optical Fiber Local Area Networks Using a Passive Star Topology," *IEEE Journal of Lightwave Tech.*, vol. LT-5, no. 12, Dec. 1987, pp 1782-1793.

[8] I. Chlamtac and A. Ganz, "Design Alternatives of Asynchronous WDM Star Networks," *IEEE ICC 1989*, Boston, June 11-14, 1989.

[9] A. Ganz and Z. Koren, "WDM Passive Star - Protocols and Performance Analysis", *IEEE INFOCOM 1991*, Bal Harbour, Florida, April 9-11, 1991.

[10] G. Coquin, K. W. Cheung and M. M. Choy, "Single- and Multiple-Wavelength Operation of Acousto Optically Tuned Semiconductor Lasers at 1.3 Microns," *Proc. 11th IEEE Int. SemiconductorLaser Conference*, Boston, Aug. 29 - Sept. 1, 1988.

[11] F. Heismann *et al*, "Narrow-Linewidth, Electro-Optically Tunable InGaAsP-Ti:LiNbO3 Extended Cavity Laser," *App. Phys. Lett.*, vol. 51, pp 164-165, 1987.

[12] M. Okai, S. Sakano and N. Chinone, "Wide-Range Continuous Tunable Double-Sectioned Distributed Feedback Lasers," *15th. Euro. Conf. on Opt. Comm.*, Gothenburg, Sweden, 1989.

[13] H. Imai, "Tuning Results of 3-Sectioned DFB Lasers," *Semicondutor Laser Workshop, CLEO'89*, Baltimore, MD, 1989.

[14] T. L. Koch *et al*, "Continuously Tunable 1.5 μm Multiple-Quantum-Well GaInAs/GaInAsP Distributed-Bragg-Reflector Lasers," *Electron. Lett.*, vol. 24, no. 23, Nov 1988.

[15] K. Kobayashi and I. Mito, "Single Frequency and Tunable Laser Diodes," *Journal of Ligthtwave Tech.*, vol. LT-6, no. 11, Nov. 1988, pp 1623-33.

[16] T. P. Lee and C. E. Zah, "Wavelength-Tunable and Single-Frequency Semiconductor Lasers for Photonic Communications Networks," *IEEE Communications Mag.*, Oct. 1989, pp 42-51.

[17] H. Kobrinski and K.-W. Cheung, "Wavelength-Tunable Optical Filters: Applications and Technologies," *IEEE Communications Mag.*, Oct. 1989, pp 53-63.

[18] S. E. Miller and I. P. Kaminow, *Optical Fiber Telecommunications II*, pp. 79-90, San Diego: Academic Press, 1988.

[19] L. Kazovsky, "Phase- and Polarization-Diversity Coherent Optical Techniques," *Journal of Lightwave Tech.*, vol. LT-7, no. 2, Feb. 1989, pp 279-92.

[20] G. Marone, P. Poggiolini and E. Vezzoni, "Polarisation Independent Detection by Synchronous Intra-Bit Polarization Switching in Optical Coherent Systems," *IEEE INTL. CONF. ON COMM. 1990*, Atlanta, GA, 16-19 April 1990, pp 1658-62.

[21] F. Heismann *et al*, "Integrated-Optic Polarization Controller with Unlimited Transformation Range," *Appl. Phys. Lett.*, vol. 57, no. 9, Aug. 1990.

[22] Y. C. Chung *et al.*, "WDM coherent star network with absolute frequency reference", *IEEE Electronics Letters*, vol. 24, no. 21, pp. 1313-1314, Oct. 13, 1988.

[23] S. Sudo, Y. Sakai and T. Ikegami, "Frequency Stabilization Scheme for DFB Laser Diodes Using Acetylene Absorption Lines in 1.51-1.55 μm," *OFC '91*, San Diego, paper FB7, 1991.

[24] L. G. Kazovsky, "Novel Relative Frequency Stabilization Technique for Multichannel Optical Communication Systems," *IEEE PTL*, vol. 1, no. 12, pp. 455-457, Dec. 1989.

[25] L. G. Kazovsky, "Experimental Relative Frequency Stabilization of a Set of Lasers Using Optical Phase-Locked Loops," *IEEE PTL*, vol. 2, no. 7, pp. 516-518, July 1990.

[26] T. Saito *et al.*, "High Receiver Sensitivity at 10 Gb/s Using an Er-Doped Fiber Preamplifier Pumped with a 0.98 μm Laser Diode," *IEEE PTL*, vol. 3, no. 6, pp. 551-3, June 1991.

[27] L.G. Kazovsky, D. A. Atlas, "Optical Phase-Locked PSK Heterodyne Experiment at 4 Gb/s", *IEEE PTL*, vol. 2, no. 8, Aug. 1990.

[28] H. Toba *et al.*, "A 100-channel optical FDM transmission/distribution at 622 Mb/s over 50 km," *Journal of Lightwave Tech.*, vol. 8, no. 9, pp. 1396-1401, Sept. 1990.

[29] R. E. Wagner *et. al.*, "16-channel coherent broadcast network at 155 Mb/s," *OFC '89*, Houston, paper PD12, 1989.

[30] B. Glance and O. Scaramucci, "Computer-controlled multichannel heterodyne optical communication system," *IEEE PTL*, vol. 3, no. 1, pp. 83-85, Jan. 1991.

[31] G. Heydt *et al.*, "CMC broadband customer access: CMC system applicaiton areas and evolution access," Fourth R1010 report, CMC-B-142-1, Sept. 1991.

[32] R. Gidron *et al.*, "TeraNet: A multi gigabit per second hybrid circuit/packet switched lightwave network," *Proc. SPIE Advanced Fiber Communications Technologies*, Boston '91, Sept. 3-4, pp. 40-48.

[33] ANSI, "Broadband ISDN ATM Aspects-ATM Layer Functionality and Specification T1S1.5/90-058R2," Aug. 27, 1990.

[34] N. R. Dono *et al.*, "A wavelength division multiple access network for computer communication," *IEEE JSAC*, vol. 8, no. 6, pp. 983-994, Aug. 1990.

[35] A. Fioretti *et al.*, "An evolutionary configuration for an optical coherent multichannel network," *GLOBECOM '90*, San Diego, CA, 2-5 Dec. 1990, pp. 779-783.

[36] L. G. Kazovsky, P. T. Poggiolini, "STARNET: an Integrated Services Broadband Optical Network with Physical Star Topology," *Advanced Fiber Communications Technologies*, Leonid G. Kazovsky, Editor, Proc. SPIE 1579, pp. 14-29 (1991).

[37] L.G. Kazovsky, "Performance Analysis and Laser Linewidth Requirements for Optical PSK Heterodyne Communications Systems", *Journal of Lightwave Tech.*, vol. LT-4, no. 4, Apr. 1986.

[38] O'Byrne, V., " A Method for Reducing the Channel Spacing in a Coherent Optical Heterodyne System," IEEE PTL, vol. 2, no. 7, July 1990.

[39] L. G. Kazovsky, J. L. Gimlett, "Sensitivity Penalty in Multichannel Coherent Optical Communications", *Journal of Lightwave Tech.*, vol. 6, no. 9, Sep. 1988.

[40] W. B. Sessa, *et al.*, "Multichannel frequency control for multilocation network applications," *OFC '91, Proceedings*, paper WH5, p. 98, San Diego, Feb. 19-22, 1991.

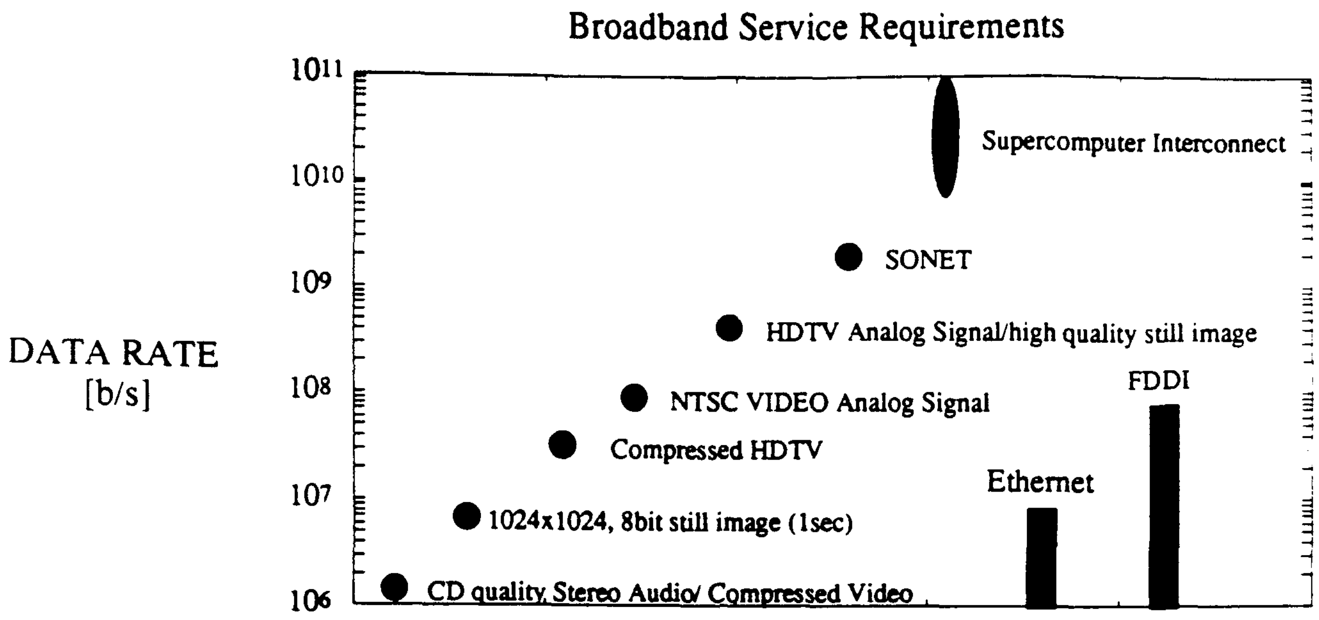
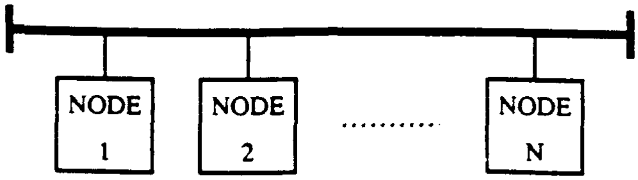
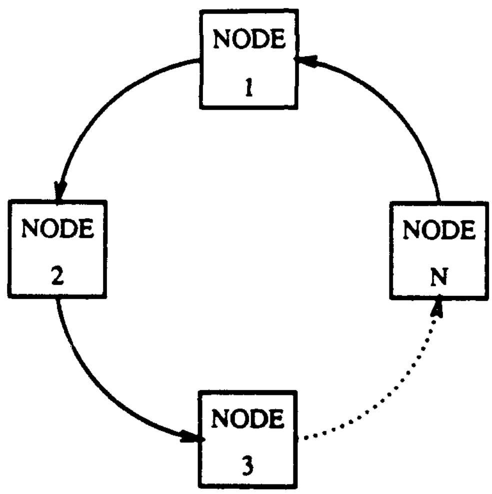


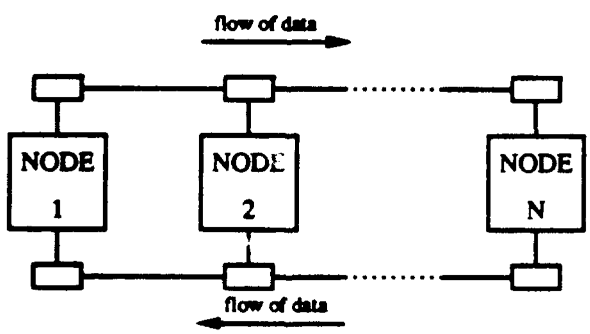
Figure 1: Data rates required for broadband services. Note limitations of existing network standards such as Ethernet and FDDI (adapted from ref. [2]).



Ethernet (broadcast bus)



FDDI (ring)



IEEE 802.6 (dual bus with reservations)

Figure 2: Current Network Topologies

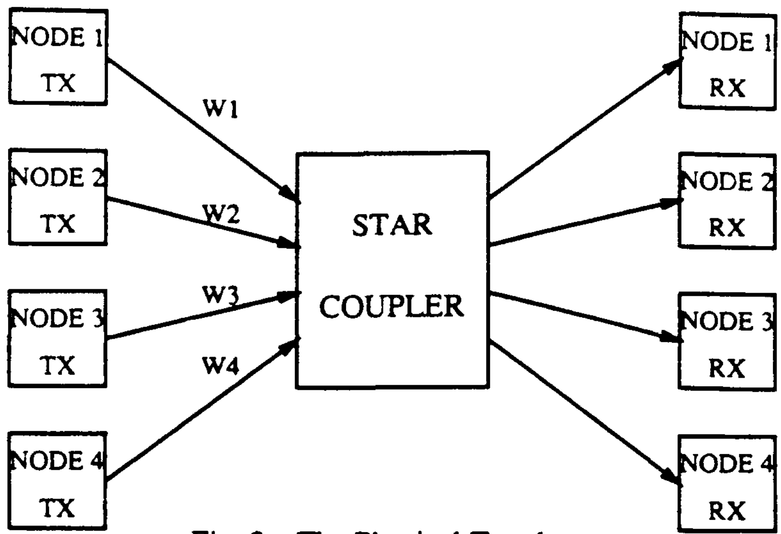


Fig. 3a: The Physical Topology

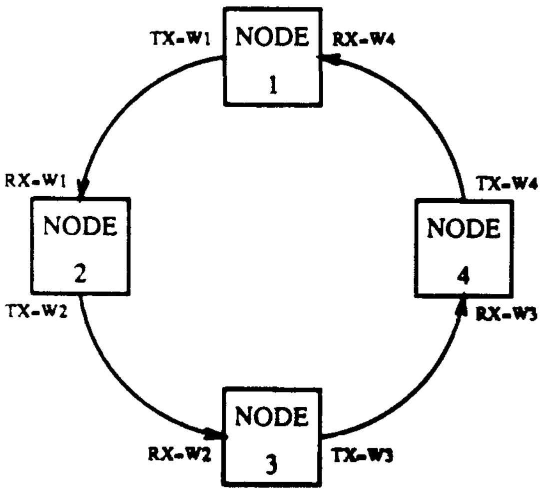


Fig. 3b: Logical Topology 1

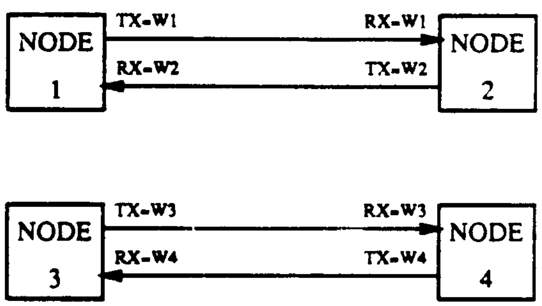


Fig. 3c: Logical Topology 2

Figure 3: The WDM Network

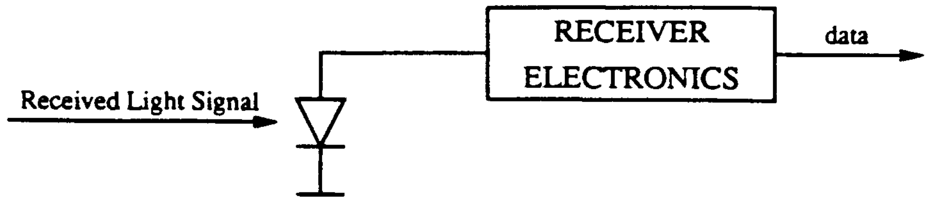


Fig 4a: Direct-Detection Receiver

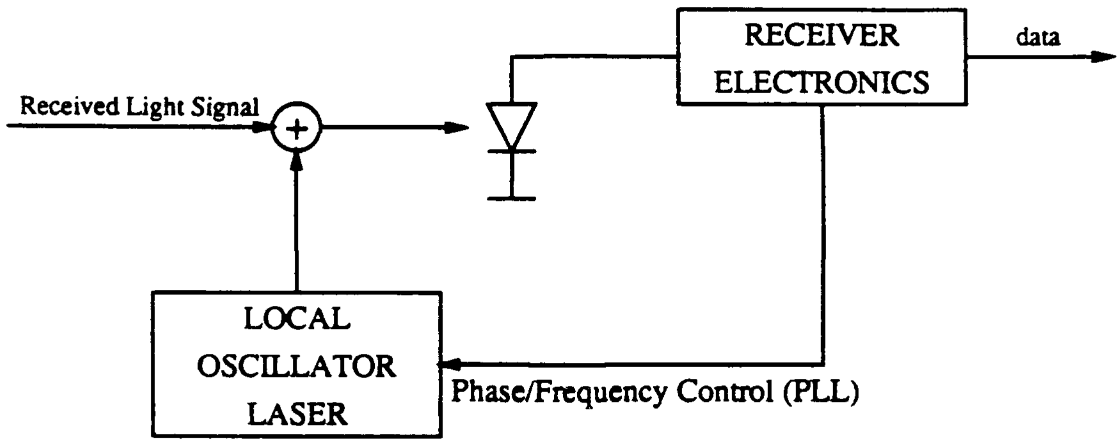


Fig. 4b: Coherent Receiver

Figure 4: Receiver Structures

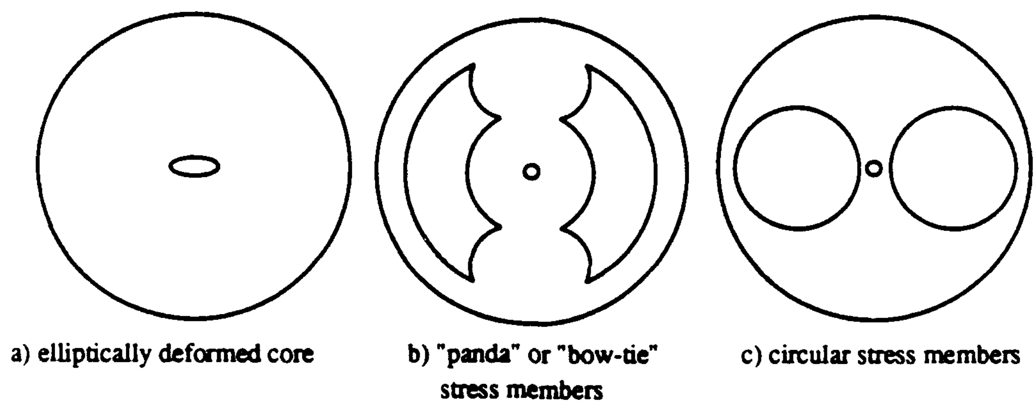


Figure 5: Examples of Polarization-Maintaining Fiber

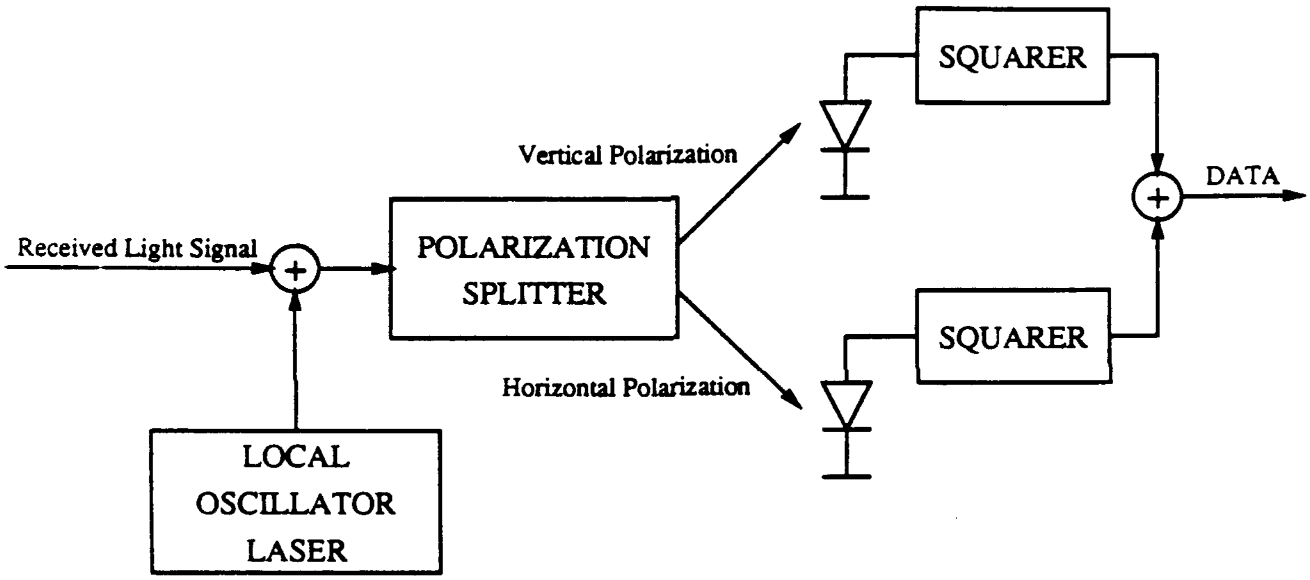


Figure 6: ASK Polarization-Diversity Receiver

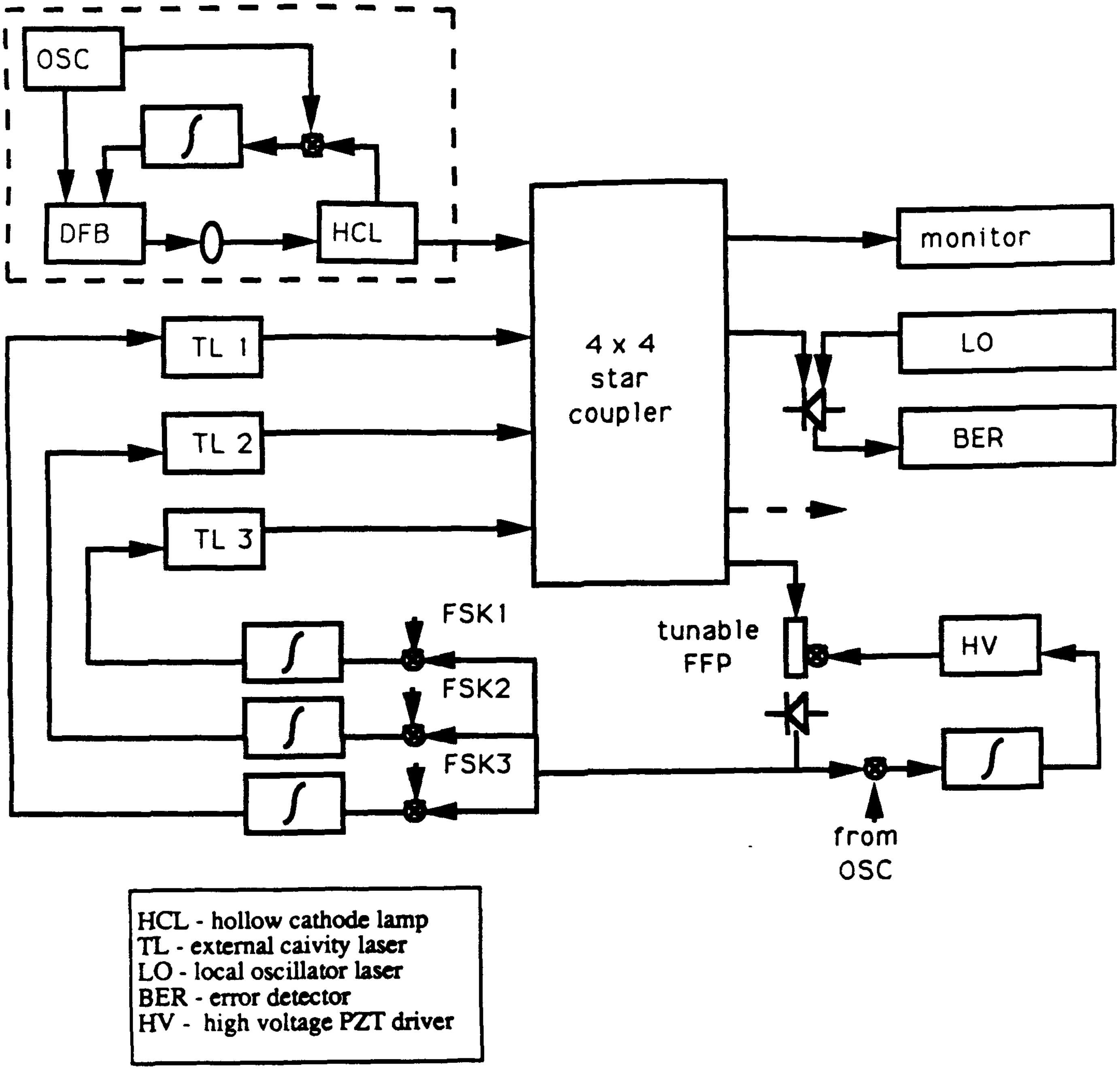


Figure 7: Absolute frequency reference experiment set-up (adapted from ref. [22]).

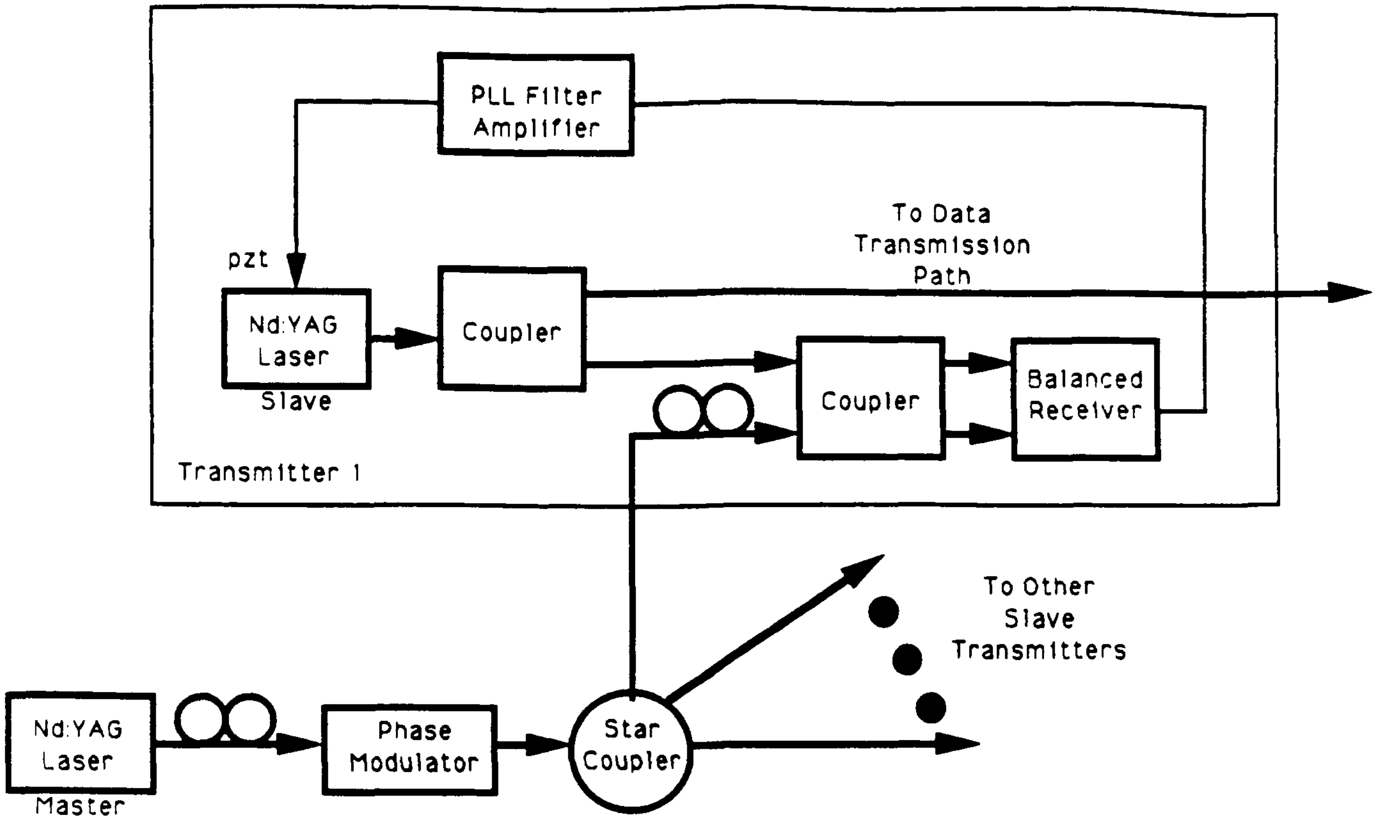


Figure 8: Experimental setup used for phase-locked frequency stabilization (adapted from ref. [25]).

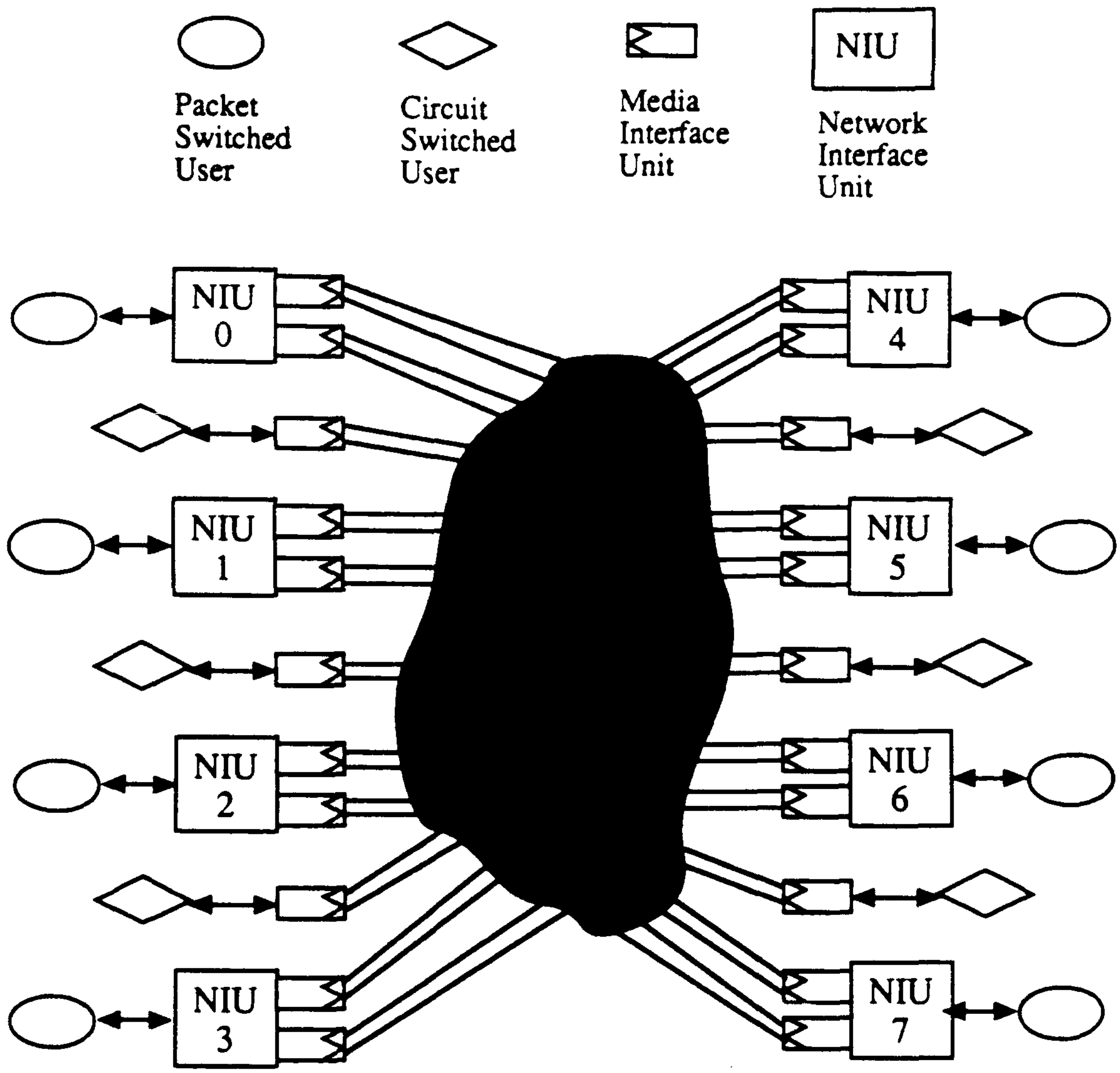
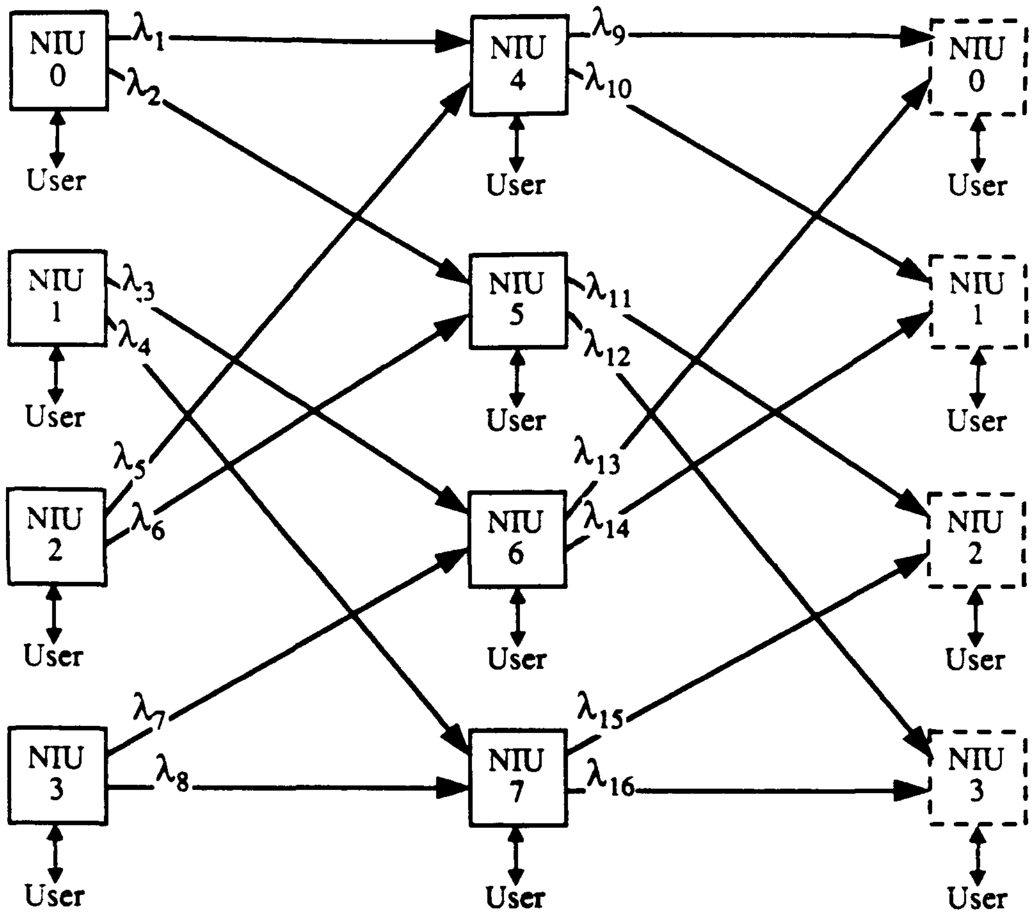


Figure 9a: TeraNet packet and circuit switching lightwave network (adapted from ref. [32]).



NIU=Network Interface Unit

Figure 9b: TeraNet eight node recirculation perfect shuffle (adapted from ref. [32]).

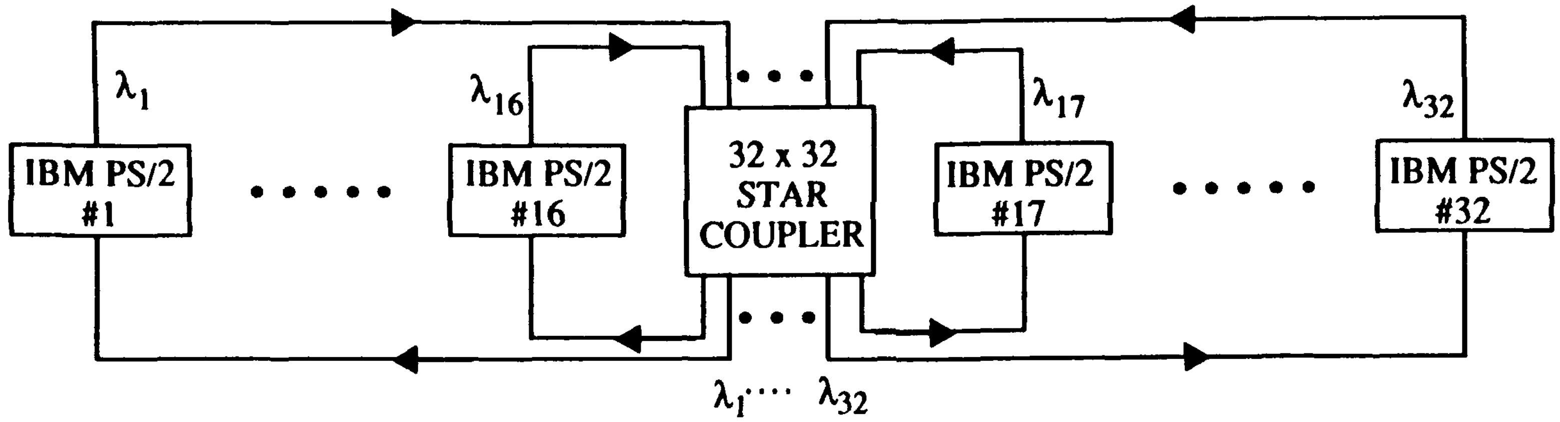


Figure 10: A block diagram of the RAINBOW Network.

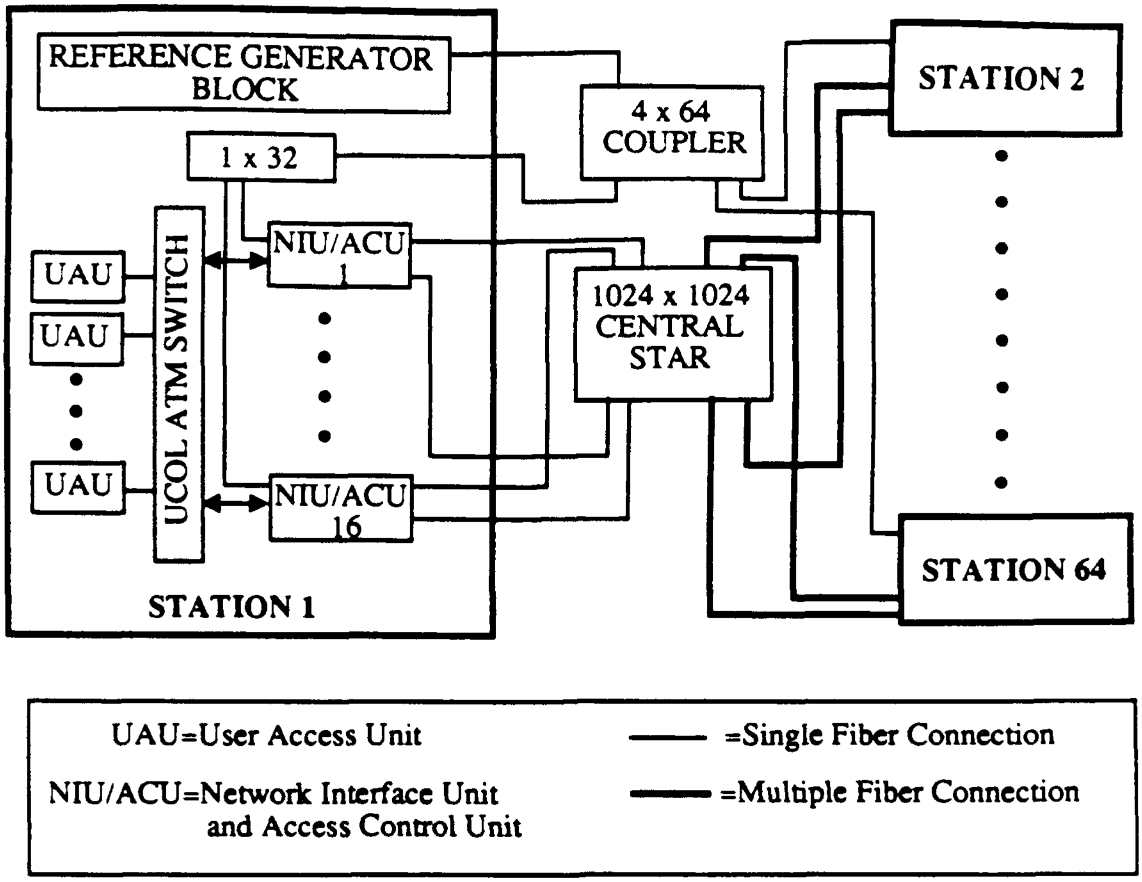


Figure 11: UCOL system block diagram (adapted from ref. [35]).

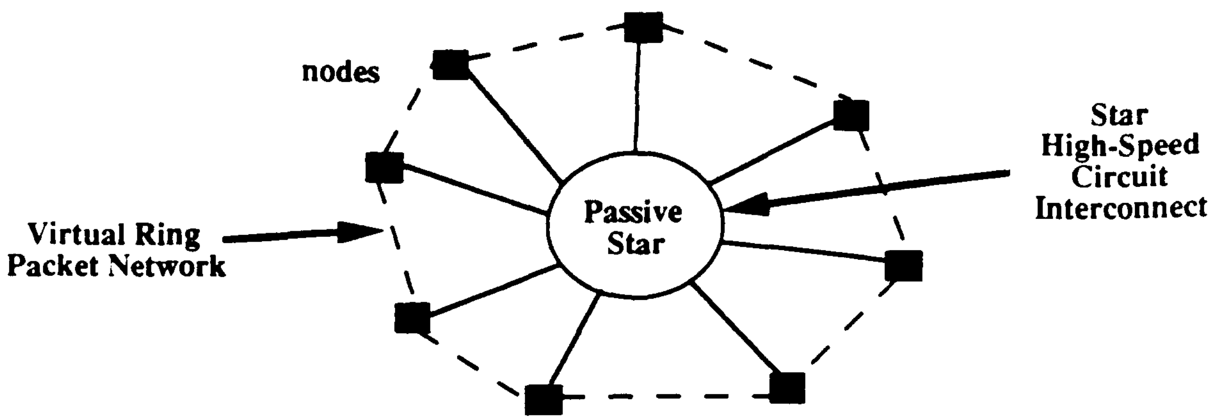


Figure 12: STARNET offers both a moderate-speed packet switch network and a high-speed broadband circuit interconnect on a physical passive star topology.

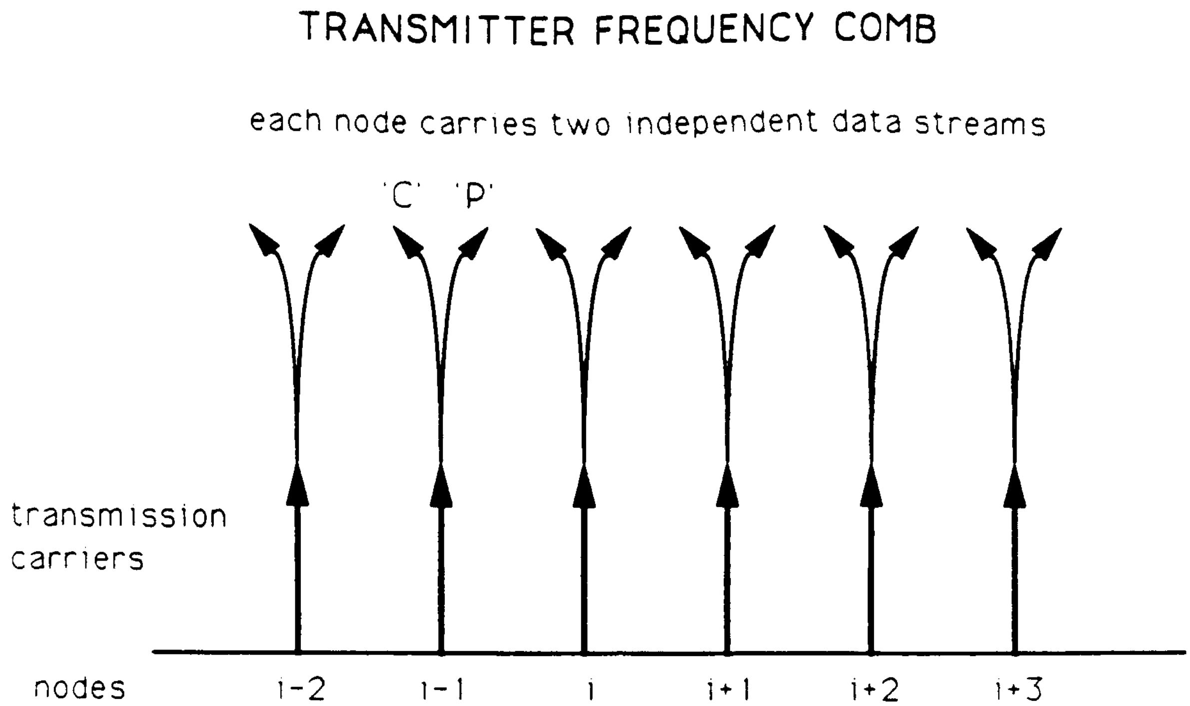


Figure 13: The node transmitter multiplexes two independent data streams onto the same lightwave carrier.

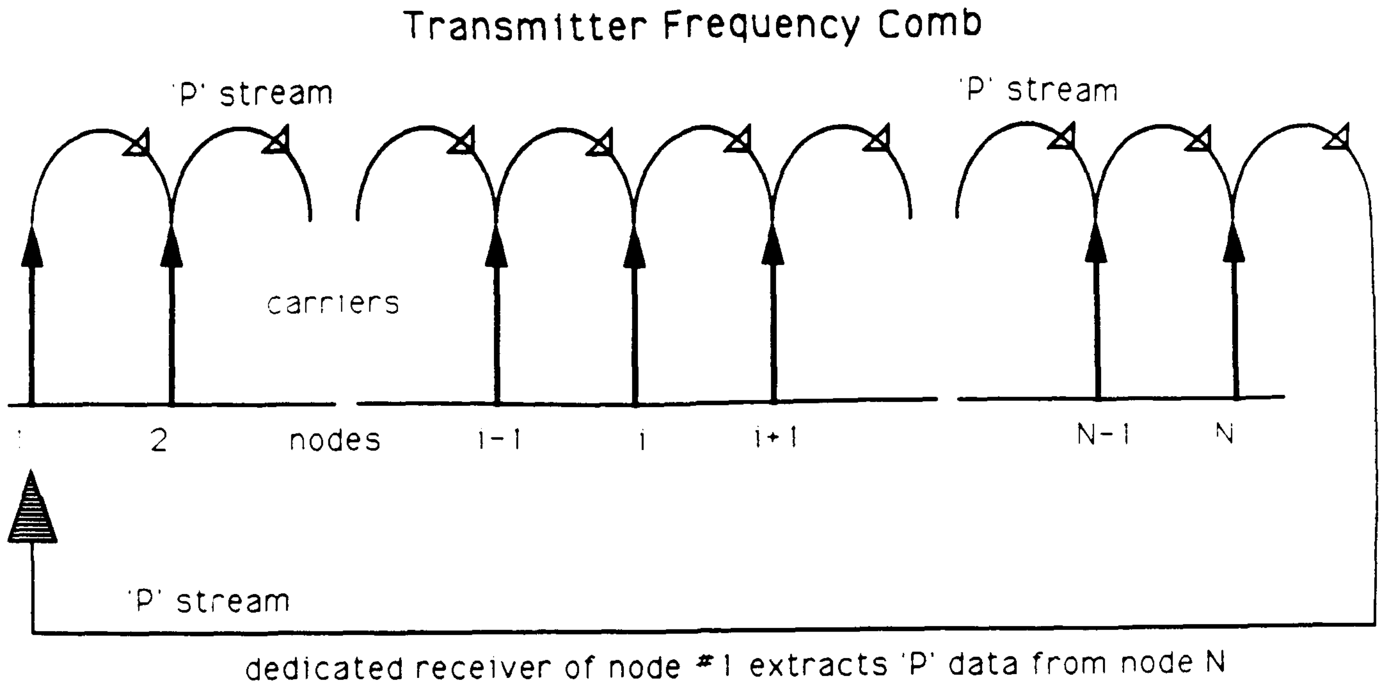


Figure 14: The first node of the chain is equipped with a receiver capable of extracting the 'P' stream of the last node in the comb, and relays 'P' data downstream.

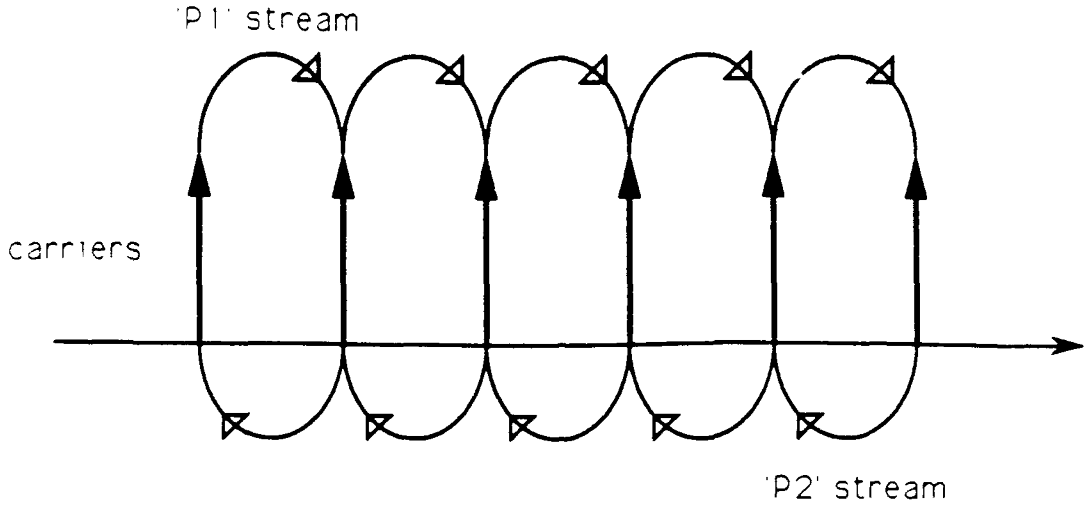


Figure 15: The connectivity allowed by a dual 'P' stream receiver permits a bidirectional store and forward chain.

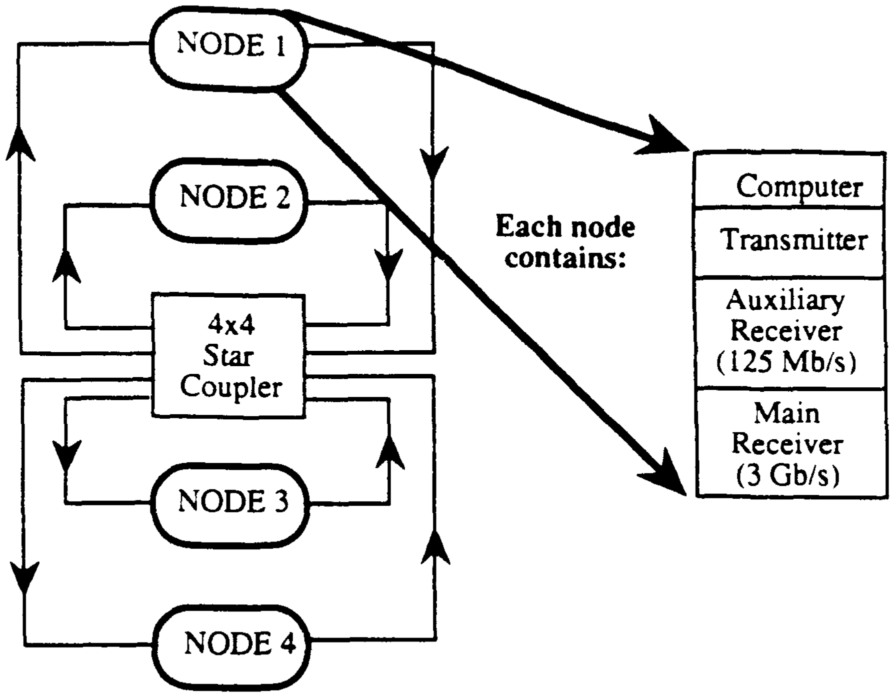


Figure 16: Physical interconnect of the four node STARNET experiment.

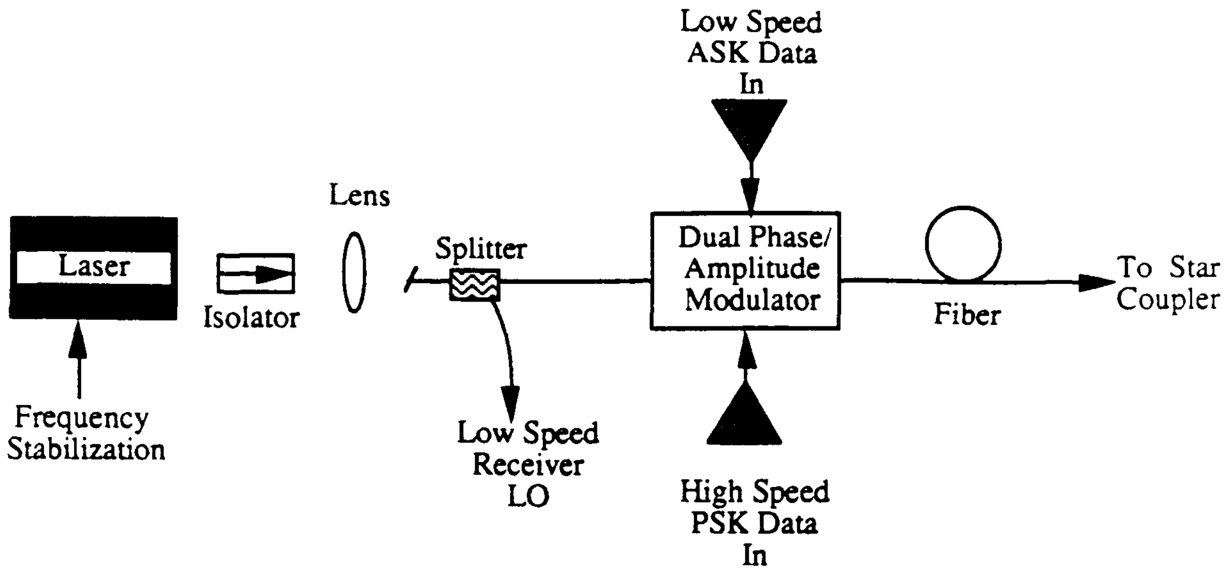


Figure 17: STARNET node transmitter.

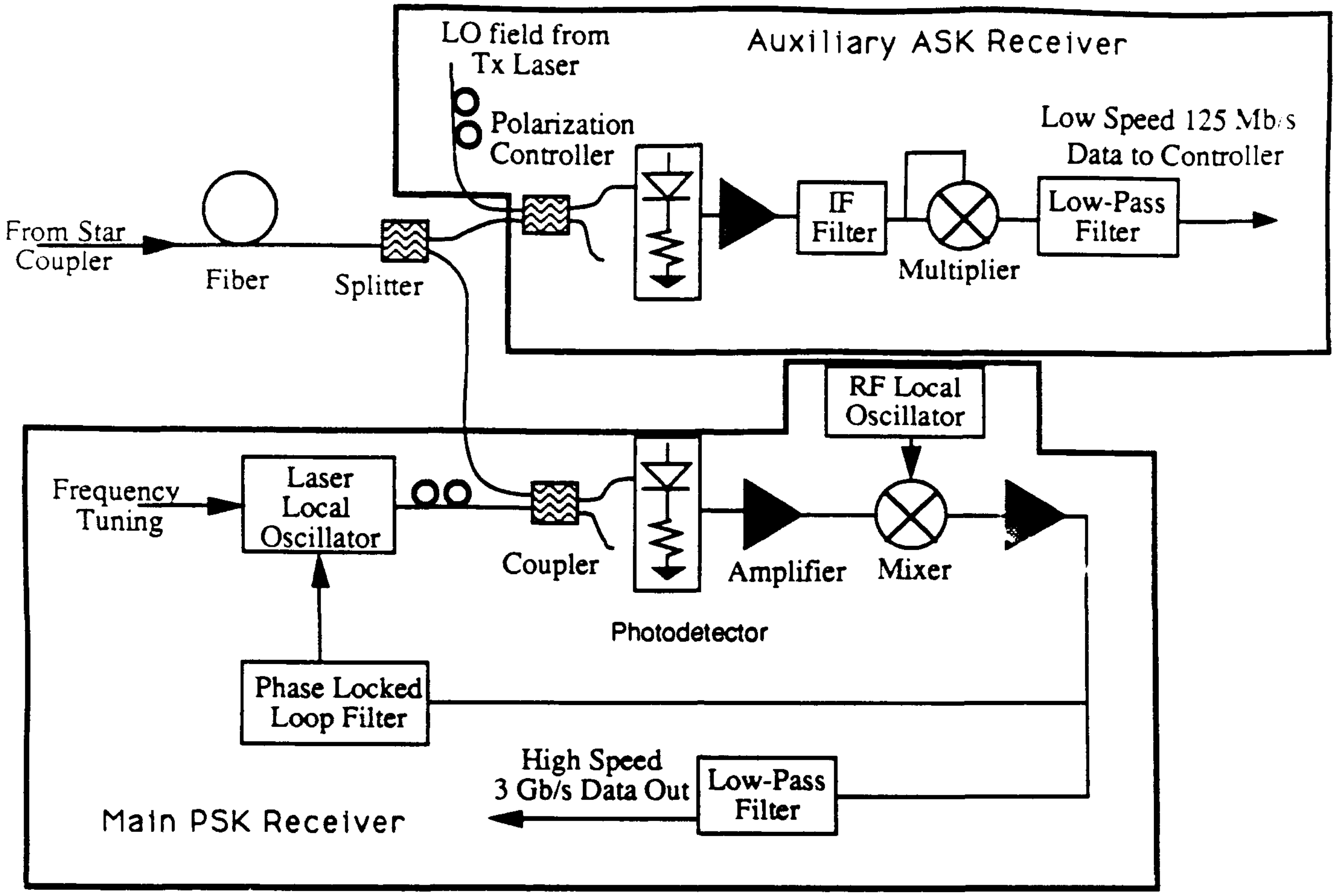


Figure 18: STARNET node receiver.

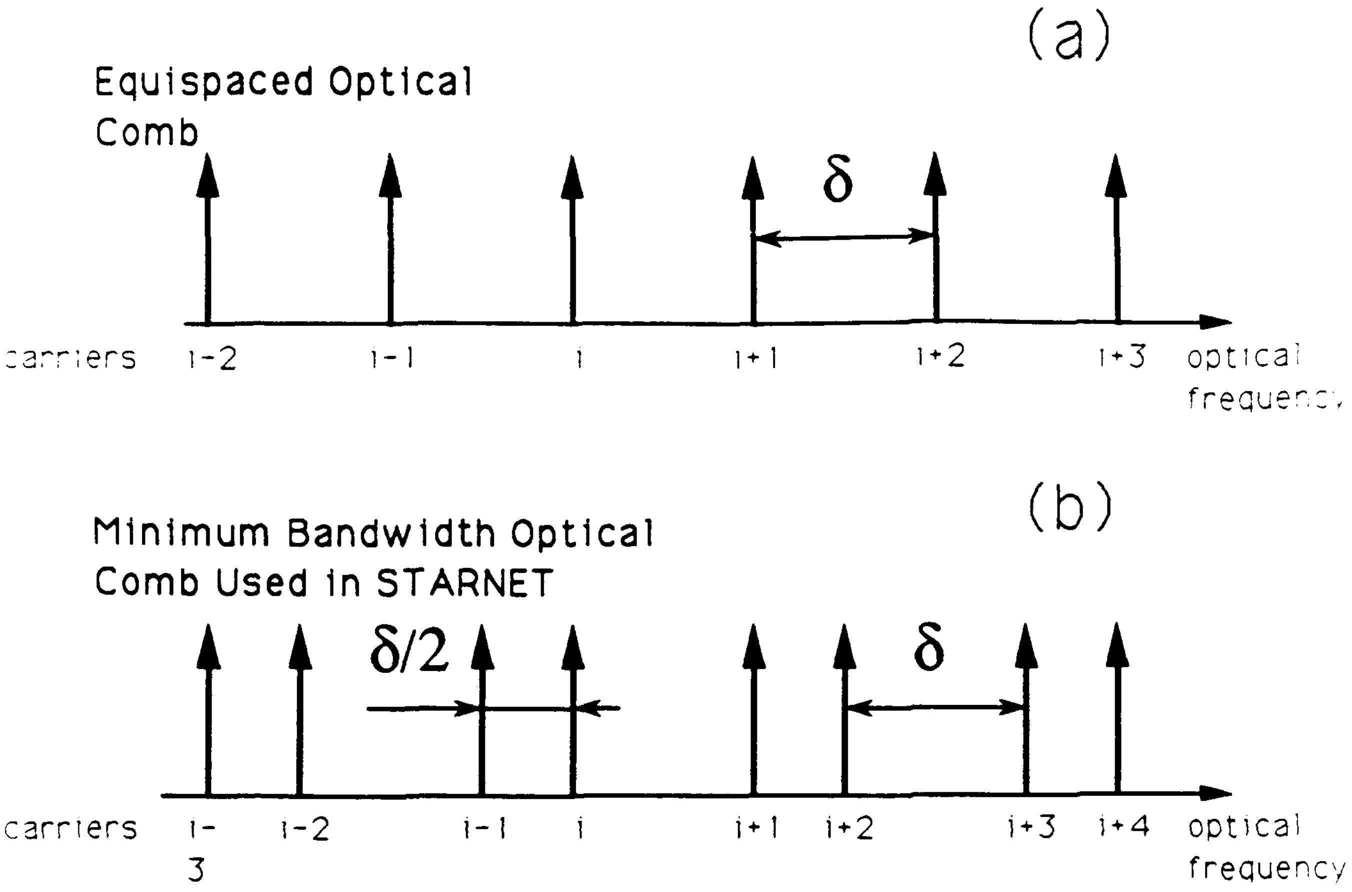


Figure 19: Equispaced and minimum bandwidth occupancy allocation of carriers in the frequency comb, for heterodyne detection.

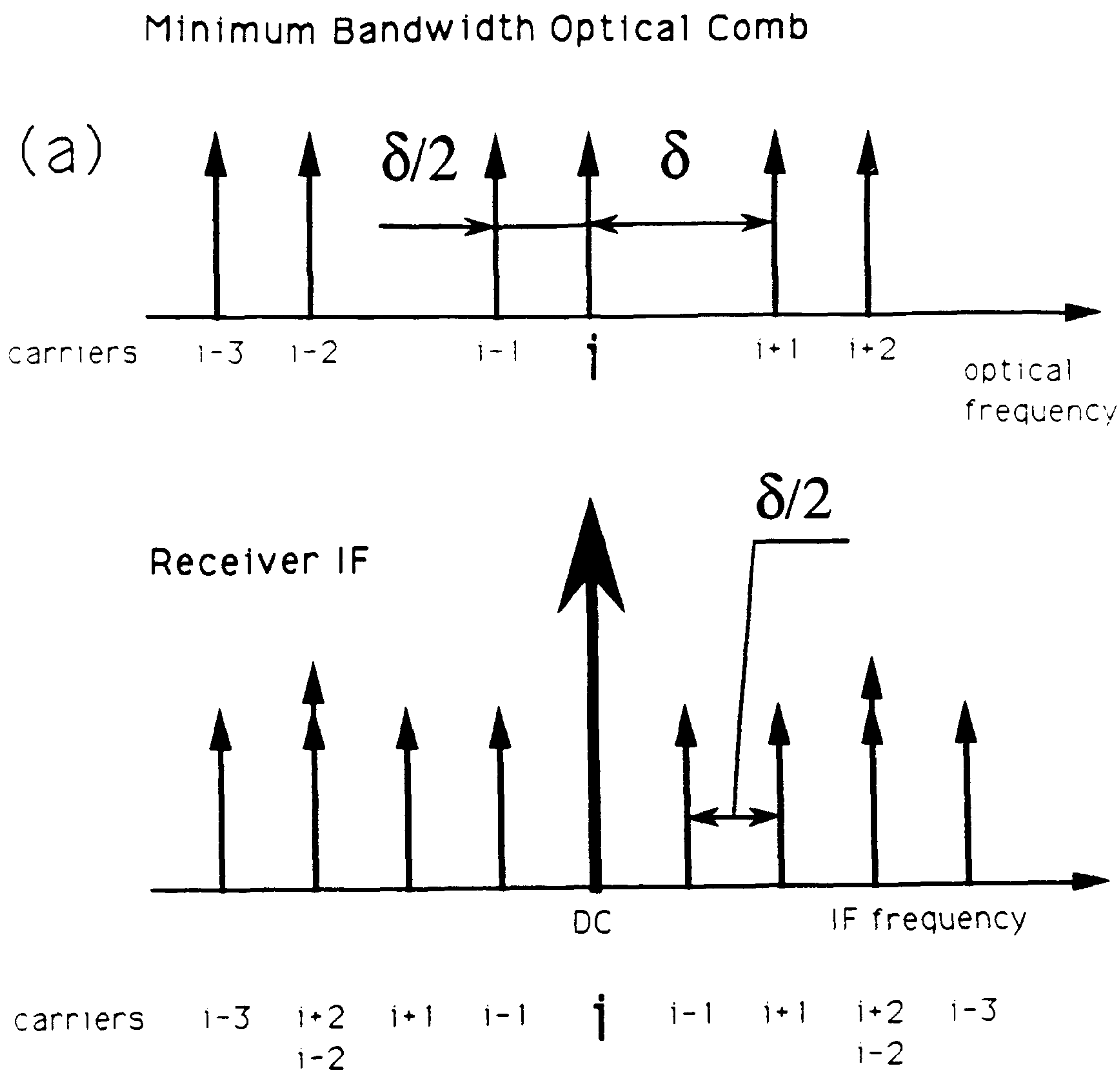


Figure 20: Carrier visibility at IF in the fixed receiver of node i, employing the node carrier as LO and minimum optical bandwidth allocation of carriers. In this case, the previous node IF is at $\delta/2$; the next node IF is at δ. The value of δ is 16 GHz in STARNET.